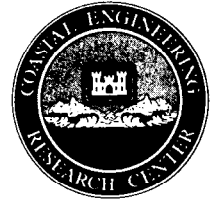


Coastal Engineering Technical Note



CAPABILITIES IN HARBOR DESIGN AND MONITORING: A CASE STUDY

PURPOSE: To present improvements in harbor design and monitoring through integration of prototype data and numerical and physical modeling of Barbers Point Harbor, Oahu, Hawaii.

INTRODUCTION: As waves travel into harbors from deep water, nonlinear processes transfer energy from the wind wave frequencies to long waves with periods on the order of several minutes. Harbor resonance is the phenomenon which occurs when the resonant periods of a harbor are equal or close to forced or incident wave periods. When the harbor is subject to these resonant periods, the amplitude of oscillations increase until the energy loss balances the energy input from the energy sources. The resonant mode with the longest period is the Helmholtz or pumping mode because the water appears to move up and down in unison throughout the harbor. Shorter period modes are characterized by an increasing number of nodes and antinodes within the harbor. Harbor resonance should be avoided or minimized in harbor planning and operation to reduce adverse effects such as hazardous navigation and mooring of vessels, deterioration of structures, and sediment deposition or erosion within the harbor.

Harbor wave response can be estimated from field measurements, numerical models, and physical models. Each of these sources of information has assumptions and limitations which restrict its utility; however, use of numerical and physical models in conjunction with prototype measurements can provide accurate engineering estimates of harbor wave response. In harbor design, or evaluation of proposed design modifications, prototype measurements are used to calibrate both the numerical and physical models and verify the wave response at selected locations within the harbor. The numerical model results are used to determine the test conditions that will be evaluated in the physical model. Incident wave conditions having little effect on the harbor are not tested in the physical model. The models provide an opportunity to test wave conditions which were not measured in the field, but are of interest from a design standpoint. The opportunity to collect data at sites other than field gage locations is made available through modeling efforts. Thus, the use of field measurements, and numerical and physical models provides an excellent example of good coastal engineering practice in the design of harbors.

BACKGROUND: The Barbers Point Harbor site is located on the southwest coast of the island of Oahu, HI. The original, privately-owned, navigation project was constructed in 1961 and consisted of a small L-shaped 21-ft-deep barge basin covering approximately

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9 acres. Due to hazardous surge under certain conditions and the limited size of the facility, the use of the barge basin was restricted.

To reduce these problems and to better serve the shipping requirements of West Oahu, a modern deep-draft harbor was constructed in 1985 under authorization of the River and Harbor Act of 1965. Both numerical and physical model studies (Durham 1978 and Palmer 1970) were conducted to evaluate design plans for the proposed deep-draft harbor. The harbor complex consists of the original barge basin, a 92-acre, 38-ft-deep main basin, and a 4,280-ft-long, 450-ft-wide, and 42-ft-deep entrance channel. A 4,700-ft-long stone wave absorber was constructed along the channel and northern corner of the basin to reduce the wave energy entering the harbor. The deep-draft harbor accommodates containerships, tankers, bulk carriers, and assorted barges. In 1989, the 16-ft-deep West Beach Marina (WBM) was constructed to accommodate 350 to 500 small craft (Figure 1).

A field monitoring study of Barbers Point Harbor was initiated in 1986 by the CERC in conjunction with the U.S. Army Engineer Division, Pacific Ocean (POD) as part of the Monitoring Completed Coastal Projects (MCCP) program. Data collection and analysis were conducted by the Scripps Institution of Oceanography as part of the Coastal Data Information Program, a network of real-time wave gages jointly sponsored and managed by the Corps of Engineers Field Wave Gaging Program and the state of California Department of Boating and Waterways. Field measurements were obtained at selected sites in the deep-draft basin, entrance channel and nearshore region.

In 1990, the state of Hawaii through the POD requested CERC to perform both numerical and physical model studies to evaluate several proposed modifications of the harbor complex to accommodate a larger deep-draft "design" vessel (i.e., an 860-ft-long containership). The proposed design modifications included (1) deepening the deep-draft harbor basin, (2) widening and deepening the entrance channel, (3) adding berthing area off the deep-draft basin, and (4) construction of a short jetty on the northern side of the entrance channel. A navigation study was included in the physical model tests to assess wave conditions due to the proposed design modifications.

Although prototype wave measurements were taken to monitor the wave response of the harbor, the measurements do not provide information as to how the modified harbor will respond to the incident wave climate. Both numerical and physical modeling were necessary to develop the existing harbor design and to evaluate future modifications. Both models have the ability to predict the resonant modes of oscillation. They also have the ability to predict the effects on the resonant modes due to changing the harbor geometry, dredging the entrance and basin, and including or modifying harbor structures. However, both models involve assumptions and limitations in simulation which require, ultimately, application of both to obtain optimal results. For instance, (a) the numerical model is based on linear wave theory, whereas the physical model includes nonlinear effects, (b) simulating numerous harbor geometries can be done more efficiently numerically than physically, (c) the numerical model is applied at prototype dimensions, whereas the physical model is a scaled-down version of the prototype, and (d) the physical model can simulate waves, currents, and navigation effects. Ultimate goals were to develop optimal designs for the deep-draft harbor and to develop insight into critical physical factors for harbor operation. The prototype

measurements were used to evaluate the predicted design performance of the previous model studies and to calibrate the present numerical and physical models to existing conditions. The results of the present models were used in conjunction to evaluate the wave response of the harbor to proposed design modifications.

MONITORING PROGRAM: The MCCC program initiated wave data collection in July 1986 and continued through March 1990. A remote automated gaging network was designed and built to acquire wave and water level data both inside and outside the harbor (Figure 1). A nondirectional waverider buoy (not shown) was placed one mile offshore of the harbor in approximately 600-ft of water to provide incident wave energy, and a four-point pressure wave gage array (S_{xy1}) was located 2,000-ft offshore at an approximate 28-ft depth to provide incident wave direction. The wave gage array was later repositioned away from the entrance channel (S_{xy2}). To collect offshore data upcoast of the harbor, a PUV wave gage was located 2,400-ft to the north of the entrance channel in an approximate 13-ft water depth. The PUV gage is composed of a pressure sensor and electromagnetic current meter combined to determine wave height, period, direction and water depth. To measure waves at other areas of interest both inside and outside the harbor, single-point pressure gages were used, including offshore and onshore gages located shoreward of the S_{xy1} array, channel entrance and channel mid-point gages located in the entrance channel, and a gage located in the south corner of the harbor. In January 1989, additional gages were installed in the north and east corners to improve spatial resolution. A sampling scheme was designed to collect both wind wave (energy) and long wave (surge) data. All gages were not continuously operational during the entire data collection period. The locations of some gages as well as the data sampling frequency and record length were modified during the data collection period. Measurements were obtained prior to and after the inclusion of the WBM.

NUMERICAL MODEL: The numerical harbor wave response model HARBD was used to estimate the wave oscillations in Barbers Point Harbor both prior to and after the completion of WBM. The model is also being applied to estimate the wave response of the proposed design modifications to Barbers Point Harbor. HARBD is a steady-state finite element model which calculates linear wave oscillations in harbors of arbitrary configuration and variable bathymetry. The effects of bottom friction and boundary absorption are included. The model was originally developed for harbor oscillations (long-period waves), and the general formulation was adapted for wind waves (short-period waves) by Houston (1981). The mathematical formulations and numerical schemes are described in detail in Chen (1984 and 1986), Chen and Mei (1974), and a user's manual (Chen and Houston 1987) is available. The model is accessible through the Coastal Modeling System (CMS) at CERC and a CMS user's manual (Cialone et al., 1991) is available.

The HARBD finite element grids generated to simulate the wave response prior to and after the completion of WBM are shown in Figure 2. The grids were designed with the length of side of each element equal to approximately one sixth of a wavelength, based on linear wave theory using a wave period of 10 sec. The semicircular boundary of the grid extends approximately 2,000-ft offshore.

Output locations were selected coincident with the prototype wave gage locations and physical model wave gages. Several additional locations through the entrance were selected

to investigate wave propagation through the entrance channel and in WBM. An advantage of the numerical model over field measurements and physical models is the ability to economically obtain harbor response data throughout the harbor. The output locations selected for the configurations prior to and after inclusion of WBM are shown in Figure 3.

The numerical model was tested at frequencies of 2.0×10^{-2} to 1.2×10^{-4} Hz or corresponding wave periods ranging from about 50 to 8,333 sec. The incident wave angle was chosen perpendicular to the bottom contours since numerical tests showed insignificant differences in results from variable wave directions for the wave periods considered. The model was tested with complete boundary reflection and no bottom friction for tests without WBM. However, to calibrate the model to the configuration including WBM, various bottom friction coefficients were used to obtain results comparable with the prototype.

PHYSICAL MODEL: The three-dimensional physical model consisted of the deep-draft harbor, barge basin, WBM, entrance channel, and offshore bathymetry to the 100-ft contour (Figure 4). It was patterned after the earlier physical model studies by Palmer (1970). Total area of the physical model is over 11,000 ft². A model to prototype scale of 1:75 (undistorted) was selected to allow proper modeling of significant harbor features, typical storm waves, longshore currents, and a "design" ship for the navigation study. The basin sides and rear were lined with wave absorbers and the northwest side allowed wave transmission through the absorber to an adjacent basin to minimize reflections and cross-basin oscillations. The model is aligned so that all harbor features, wave gages, and simulated wave conditions correspond with those in the prototype (Briggs, Lillycrop, and McGehee 1992).

Waves were generated with CERC's directional spectral wave generator (DSWG), an electronically-controlled, electromechanical system, which allows generation of waves typical of those occurring in nature. The generator is 90-ft long and consists of 60 paddles. Capacitance wave gages were used to measure surface elevations at the gage locations shown in Figure 4. The first 9 locations correspond to the prototype locations. The remaining locations correspond with various output locations in the numerical model and were included to better quantify harbor wave response. Eight prototype wave conditions, measured between 1986 and 1990, were simulated in the physical model. Simulated wave period, significant wave heights, and directions range from 6 to 20 sec, 6 to 10 ft, and S30W to West with directional spreading up to 10 degrees, respectively. Selection of wave conditions was based on (1) waves measured after WBM opened in July 1989 and repositioning of the wave gage array S_{xy2} (gage 2 in Figure 4), (2) the largest measured wave heights, (3) a representative range of wave period and direction, (4) maximum number of operational field gages for comparisons, and (5) wave directions which could be reproduced within the constraints of the physical model. Each case is representative of wave conditions which could have occurred prior to or after inclusion of WBM. A MLLW water level was used for all cases.

PROTOTYPE HARBOR RESONANCE: A transfer function estimate was used to express the relationship between wave energies outside the harbor (the input) and conditions inside the harbor (the output). Transfer function estimates were calculated for all gages in the

harbor using incident conditions from the S_{xy2} array. Estimates were based on autospectral and cross-spectral analysis of the gage data.

Data collected from February 1989 to March 1990 were analyzed for long-period harbor resonance by Okihiro (1991). This time frame included harbor configurations with WBM open and closed. Plots of prototype data for each gage located inside the harbor are given for both configurations in Figure 5. The four gages exhibit the long-period Helmholtz mode at 1024 sec when WBM was open and 910 sec when WBM was closed. The presence of WBM also corresponds to the appearance of a resonant peak at 670 sec.

At shorter wave periods, significant differences between the two configurations are most noticeable at the Channel Mid-point gage. With WBM closed, a broad peak is centered at 167 sec. After WBM is opened, three resonant peaks appear centered at 200, 167, and 125 sec. This is because this gage is located opposite the entrance to WBM, which changes the physical length of the basin at this location. In the South, East, and North corners, the resonant modes appear unchanged by the addition of WBM.

The dominant resonant peaks in the harbor basin appear at 132 and 110 sec. The presence and absence of these resonant peaks at various locations in the basin indicate node and antinodes typical of standing waves. The 132-sec mode is energetic at the North and South corners; however, energy at the East corner and Channel Mid-point is negligible. This indicates a nodal line between the North and South corners extending from east to west across the harbor. The 110 sec mode is energetic at the South and East corners whereas energy at the North corner is absent. This implies a nodal line runs from the North corner to a point along the south-east wall at this wave period (Okihiro 1992).

MODEL RESULTS: Numerical model wave height amplification factors (i.e., the ratio of the wave height to the incident wave height) from output locations corresponding to the channel midpoint, north, east, and south prototype gage locations are plotted in Figure 6 for the harbor configurations with the WBM open and closed, analogous to Figure 5. Magnitudes are slightly larger than corresponding prototype values since no energy losses were included in these simulations (i.e., no bottom friction and perfect boundary reflection). In general, the agreement is very good between the numerical model predictions and the prototype measurements for both harbor configurations.

The numerical model was calibrated and results are plotted with the physical model results, and the field measurements after WBM was opened (Figure 7). Numerical model magnitudes are reduced due to grid refinements and the inclusion of bottom friction for these simulations. The physical model included "built in" friction and reflection since model construction was based on the prototype harbor. The physical model results are very good considering the results were based on averaging over the eight prototype wave events simulated in the physical model; whereas, the prototype data were based on averaging over 58 to 117 wave events, depending on the number of wave records measured at each location. Both numerical and physical models compare well in predicting the resonant modes found in the prototype data.

Both model results also revealed resonant modes of oscillation which occur in the barge basin and WBM. Since prototype measurements are unavailable in these areas, the model results provide valuable guidance for evaluating navigation and mooring in these areas. Also, this information was used to verify that proposed modifications would not adversely impact the response of the barge basin and the WBM.

DISCUSSION: Both physical and numerical models provided valuable information about the harbor which was not available from the prototype measurements. For the existing harbor, the models filled in gaps in the data base. One of the proposed modifications was widening and/or flaring the entrance channel to improve the navigability for the larger "design" vessel. Both models showed that this would increase the amount of wave energy entering the harbor to an unacceptable level. Adding an 1100-ft square berthing area off the deep-draft harbor changed the resonant modes of the east and south corners due to the increase in the characteristic length of the larger basin.

Physical and numerical models have strengths and limitations which must be recognized in making sound engineering judgements. Although both models can predict resonant modes of oscillation fairly well, the numerical model predicts the very long-period resonant modes better than the physical model (Figure 7). Long-period modes may be under-represented in the physical model because duration of the data collection is limited by economic concerns or by the size of the model. Physical models, however, more accurately predict the shorter period waves. This is due to "built in" dissipating factors in the physical model; whereas, in the numerical model, choosing correct reflection and absorption coefficients requires calibrated estimates.

Additional numerical model strengths include (a) ease of model setup and changes once good charts are provided, (b) availability of data throughout the modeled harbor grid which permits visualization of the wave response over the entire grided region, (c) quick response time, and (d) less cost to run the model. Limitations include simulation with unidirectional regular waves without directional spreading effects and lack of good reflection coefficient and bottom friction data for accurately calibrating the model.

Similarly, additional physical model strengths include the ability to simulate (a) directional wave spectra, (b) nonlinear wave-wave transformation as waves travel into harbors, (c) reflection, transmission, and overtopping of structures, (d) dissipation due to bottom friction within scale and depth limitations, (e) currents, and (f) navigation studies with model ships.

This CETN has demonstrated that the use of field measurements, and physical and numerical models provide an excellent example of good coastal engineering practice in designing and evaluating proposed modifications of harbors. The combination of all three verified the resonant modes of oscillation and quantified their effect on navigation and mooring conditions. At other sites, the degrees to which each of the three tools will be used will have to be tailored to the specific physical conditions. Adequate prototype data should be collected to calibrate/validate numerical and/or physical models to predict the effect of proposed modifications on harbor response.

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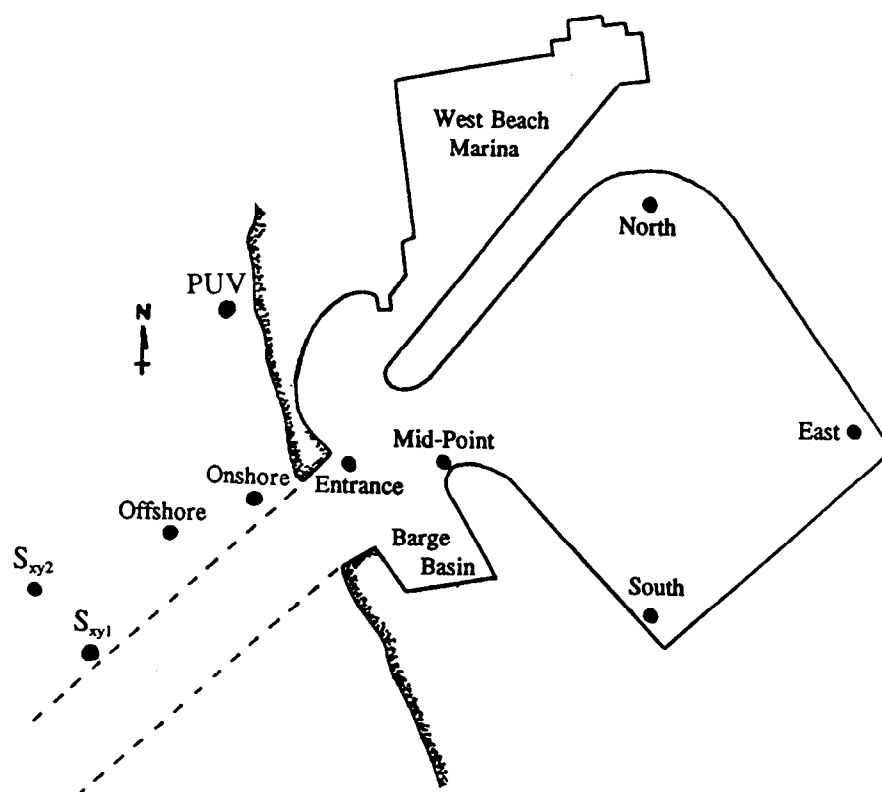
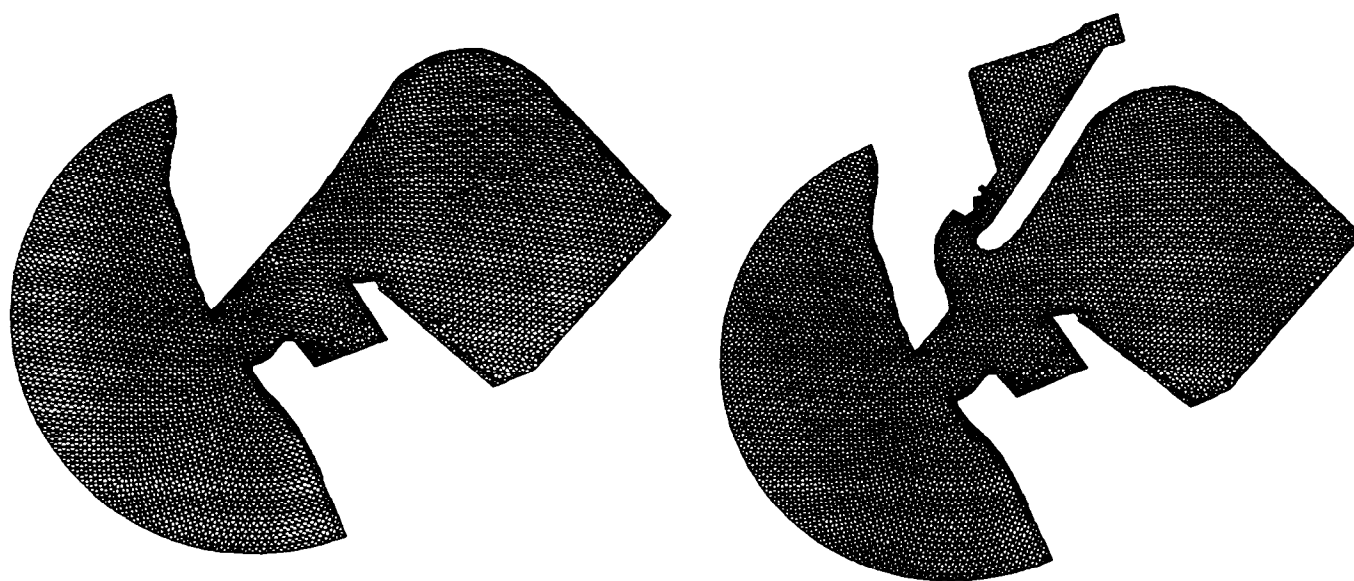


Figure 1. Barbers Point Harbor, Oahu, HI



a) Excluding West Beach Marina

b) Including West Beach Marina

Figure 2. Numerical Model Grids

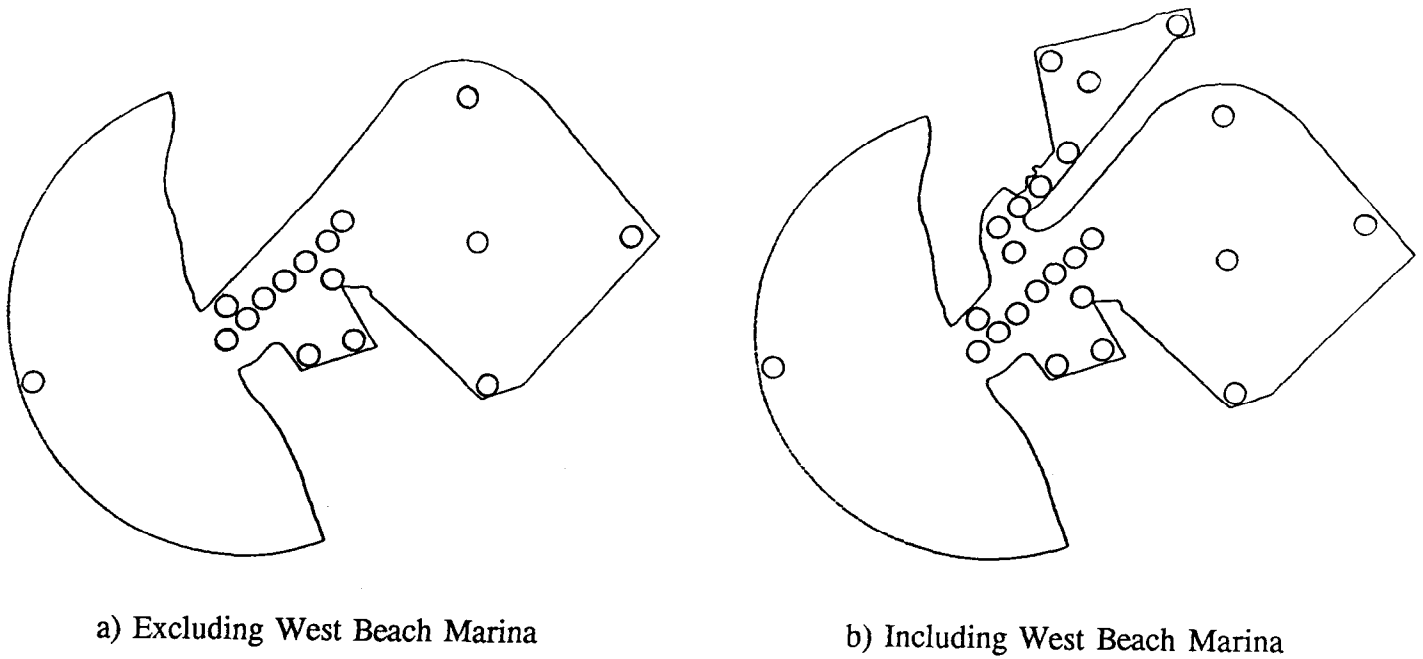
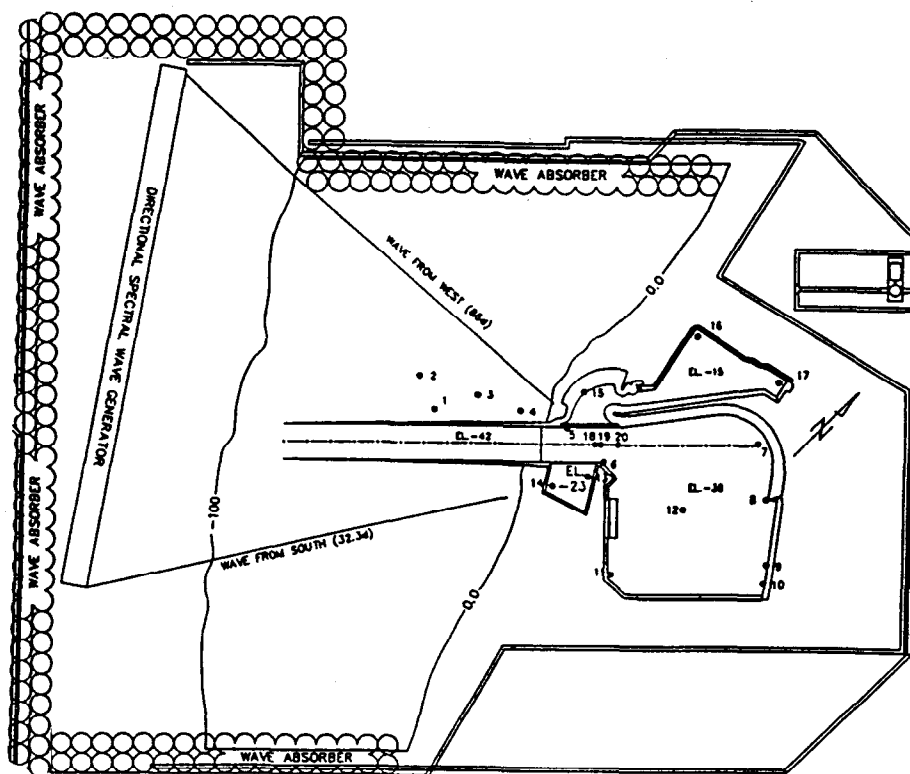


Figure 3. Numerical Model Output Locations



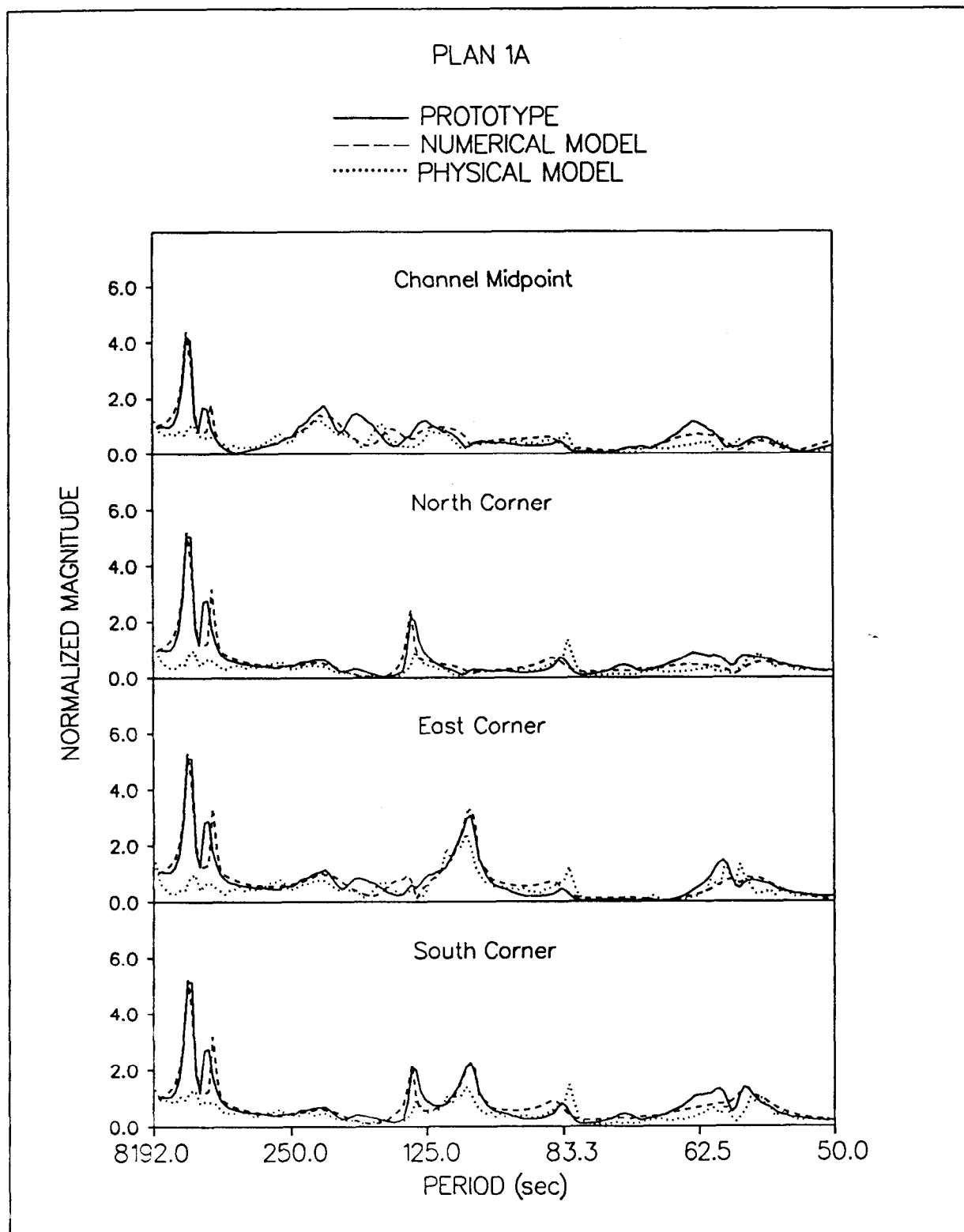


Figure 7. Comparison of Prototype Measurements, Numerical Model, and Physical Model